

# Space cowboys odyssey: beyond the Gould Belt

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**Abstract.** We present our new advanced model for population synthesis of close-by cooling NSs. Detailed treatment of the initial spatial distribution of NS progenitors and a detailed ISM structure up to 3 kpc give us an opportunity to discuss the strategy to look for new isolated cooling NSs. Our main results in this respect are the following: new candidates are expected to be identified behind the Gould Belt, in directions to rich OB associations, in particular in the Cygnus-Cepheus region; new candidates, on average, are expected to be hotter than the known population of cooling NS. Besides the usual approach (looking for soft X-ray sources), the search in 'empty'  $\gamma$ -ray error boxes or among run-away OB stars may yield new X-ray thermally emitting NS candidates.

**Keywords:** neutron stars, thermal evolution, population synthesis, X-ray observations

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## INTRODUCTION

More than 10 years after the discovery of its brightest member RX J1856-3754 [1], a group of seven radio-quiet isolated neutron stars (NSs) detected by ROSAT gained an important place in the rich zoo of compact objects. Together with Geminga and several close-by young radio pulsars, these objects form the local population of cooling NSs. Studies of this group of sources already provided a wealth of information on NSs physics (see e.g. [2, 3, 4] for recent reviews).

Since 2001 the number of known close-by radio-quiet NSs has not been growing despite all attempts to identify new candidates. Partly this is due to the fact that all these searches are blind. To advance the identification of new near-by cooling NSs it is necessary to perform a realistic modeling of this population.

To investigate the population of close-by young cooling NSs the method of population synthesis is used here. In this short note an advanced population synthesis model is briefly discussed for the population of close-by ( $< 3$  kpc) isolated NSs which can be observed via their thermal emission in soft X-rays (the detailed description and full analysis of new results will be presented elsewhere [5]). Previously our models were applied to confirm the link between the seven radio quiet NSs (the Magnificent Seven) and the Gould Belt [6] (Paper I), to study distribution of NSs in the Galaxy and in the solar vicinity [7] (Paper II), and to test theories of thermal evolution of NSs [8] (Paper III). The major interest of the present study is to get a hint how to find more objects of this type.

## THE NEW MODEL

The main physical ingredients which constitute our population synthesis model are:

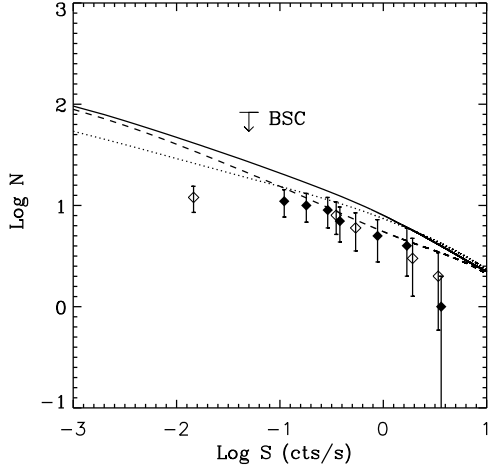
- (A) the initial NS spatial distribution and the NS birth rate;
- (B) the kick velocity distribution of the NSs;
- (C) the Galactic gravitational potential;
- (D) the NS mass spectrum;
- (E) the NS cooling curves;
- (F) the NS surface emission in X-rays;
- (G) the interstellar absorption of X-rays;
- (H) the properties of the X-ray detector.

Ingredients B, C, E, and F are unchanged with respect to our previous studies. The ingredients A, D, G, and H are modified. The new detailed initial spatial distribution of NS progenitor is one of the main feature of the advanced model. Now we take into account inhomogeneities of the distribution of massive stars up to 3 kpc from the Sun (OB associations and other stellar groups). We use new ISM element abundances and photoelectric cross sections from [9], and apply two new variants of the ISM 3D distribution. We perform more accurate calculations of the detector response than it was in Papers I-III. Some details about these modifications can be found in [10, 5].

At each time step we consider eight NS masses with corresponding cooling curves. The overall result of simulated evolutionary tracks, from birth till the time when the temperatures falls below  $10^5$  K, is normalised by the mass distribution as well as by birth rates.

## RESULTS

At first, it is necessary to note that significant advances made in the new model do not change significantly the main results (in the first place the Log N – Log S distribution) in comparison with our early studies. In particular, we tested a new variant of NS mass spectrum in which the peak at  $\sim 1.4 M_{\odot}$  is smeared out. This modification has insignificant influence on the Log N – Log S distribution. The use of more realistic abundances of elements in the ISM and more precise calculation of the detector response also have minuscule effects (see [10]). Finally, the new initial spatial distribution of NS progenitors and two new models of the ISM distribution have visible, but not crucial influence on the Log N – Log S distribution (see, Fig. 1 for the effect of the new ISM models). With the new initial spatial distribution, cooling curves from [11] (model I in Paper III), and the new ISM model based on data from [12] (dashed line in Fig. 1) we can successfully fit data points at all fluxes. Our prediction about the number of unidentified cooling NSs in the solar vicinity is generally unchanged with respect to our previous calculations. However, now in addition to calculations of absolute numbers of unidentified objects, we can address the question of their 3D distribution, and their age distributions for different fluxes.

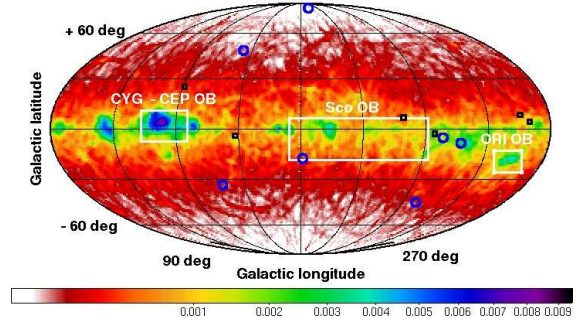


**FIGURE 1.** Log N – Log S for different X-ray absorbing ISM models. All curves are plotted for the new initial spatial distribution. Solid curve: old, simple analytical ISM model as e.g. in Paper III. Dotted curve: new improved analytical ISM model; dashed curve: ISM model which includes the extinction study by Hakkila (1997).

New results obtained in this study are related to artificial maps of cooling NS distributions on the sky, and to age and distance distributions of sources in different flux ranges. These new data give us an opportunity to discuss a strategy to identify new candidates.

On the calculated maps sources appear to be concentrated towards the Galactic plane and the plane of the Gould Belt (see Fig. 2). Few objects are expected to be found at latitudes higher than  $30^{\circ}$  (however, here we do not take into account runaway and hypervelocity progenitors, which can be important to study such objects as Calvera [13]). Inside  $\pm 30$  degrees from the Galactic plane the distribution of sources is dominated by NSs from relatively close, rich OB associations (Sco OB2, Cyg OB7, Cep OB3, and Ori OB1).

Interplay between source distribution and 3D ISM structure allows us to make predictions on which directions are most promising for looking for new cooling NSs. Our results indicate that isolated cooling NSs should be searched in directions of OB associations such as Cyg OB7 and Cep OB3. Analysis of the age distributions of sources in different flux ranges shows, that on average, new candidates should be slightly hotter than the Magnificent Seven as they are younger (this is an obvious selection effect: it is easier to detect hotter sources from larger distance observing through absorbing ISM).



**FIGURE 2.** The expected number density of isolated neutron stars with thermal X-ray emission in units of numbers per square degree. The galactic map is in Mollweide projection. Only sources with ROSAT PSPC count rates larger than  $0.05 \text{ cts s}^{-1}$  are considered, the same value as used in Paper II in their Fig. 6. The simulation was done for new initial progenitor distribution, new abundances, old mass spectrum and the analytical ISM model, thus corresponds to the dotted Log N – Log S curve in Fig. 1. Circles mark the positions of the Magnificent Seven, and squares – the positions of close young radio pulsars with detected thermal X-ray emission.

Analysing the distance distribution of sources with different fluxes, we note the following feature. While for large fluxes (brighter  $0.1 \text{ ROSAT counts per second}$ ) most sources are situated in the region  $\sim 200 - 400 \text{ pc}$  (ie. in the Gould Belt), for fainter objects the picture is different. At fluxes below  $\sim 0.1 \text{ cts s}^{-1}$  one expects to see mostly sources behind the Gould Belt. These general features are very important, as they indicate that new, still unidentified “cowboys” are expected to be young objects behind the Gould Belt.

## DISCUSSION

The main aim of this study is to make some advances in the strategy for searching for new isolated cooling NSs. According to our results, new candidates expected to be identified at ROSAT count rates  $< 0.1 \text{ cts s}^{-1}$  should be young objects born in rich OB associations behind the Gould Belt. Most of the recent studies [14, 15, 16] looked for new candidates far from the galactic plane. It seems that this is not very promising. Our results indicate that new cooling NSs should be searched in directions of OB associations such as Cyg OB7 and Cep OB3.

Considering sky coverage the ROSAT All Sky Survey is currently the best choice to look for new “cowboys” in the Cygnus-Cepheus region which is, according to our results, the most promising area. However, the relatively large positional error circle of ROSAT usually includes many possible optical counterparts, especially at these low galactic latitudes. Furthermore one has to exclude variable X-ray sources to find isolated cooling NSs. In this respect the recently published XMM-Newton Slew Survey may become an important database. A major step can be expected from the planned eROSITA all sky survey which - compared with the ROSAT all sky survey - will provide a factor of  $\sim 10$  in soft X-ray sensitivity and factor of  $\sim 4$  in energy resolution [17].

Some of unidentified  $\gamma$ -ray sources (already observed by EGRET and forthcoming due to AGILE and GLAST) can be identified as cooling NSs as it was with Geminga and 3EG J1835+5918. In particular, GLAST observations of the 56 EGRET error boxes studied in [18] and later cross-correlation with the ROSAT (or/and XMM) data can result in new identification of cooling NSs.

Another possibility to find new isolated coolers is to search for (un)bound compact companions of OB runaway stars. More than one hundred OB runaway stars are known in a 1 kpc region around the Sun [19]. They are characterized by large spatial velocities or/and by large shifts from the galactic plane. Two main origins of these large velocities are currently discussed: dynamical interaction and explosion of a companion in a close binary system. The latter case is interesting for the discussion of search for new close-by cooling NSs.

A binary can survive after the first SN explosion in, roughly, 10-20% of cases. Then one expects to have a runaway system consisting of an OB star and a compact object (most probably a NS). A young NS can appear as a radio pulsar. In [20] and [21] the authors searched for radio pulsar companions of  $\sim 40$  runaway OB stars. Nothing was found. This result is consistent with the assumption that in less than 20% cases OB stars have radio pulsar companions. Still, it is interesting to speculate that runaway massive stars can have cooling radio quiet NS as companions. Then a companion can be identified as a source of additional X-ray emission.

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